Space-Time Adaptive Matched-Field Processing (STAMP)

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Abstract

Space-time adaptive processing (STAP) is two-dimensional adaptive filtering employed for the purpose of clutter cancellation to enable the detection of moving targets. It has been a major focus of research activity in radar applications for which the platform is in motion, e.g., airborne or space-based systems. In this setting, an antenna sensor array provides spatial discrimination, while a series of time returns or pulses form a synthetic array that provide Doppler (velocity) discrimination.

The application of STAP for the mobile towed-array sonar system is non-trivial because of the complex multi-paths in the underwater environment. On the other hand, Matched-field processing (MFP) that uses a propagation code to predict the complex multi-path structure and coherently combines it to provide range/depth discrimination has been studied and demonstrated. MFP with a synthetic array (a series of snapshots) to estimate the source velocity and localize source in range and depth has also been demonstrated [1].

STAMP combines the adjacent-filter beamspace post-Doppler STAP [2] and MFP to provide improved performance for the mobile multi-line-towed-array sonar applications. The processing scheme includes: transforming phone time snapshots into frequency domain, at each frequency bin forming horizontal beams in the directions of interest for each towed line, then combining signals from multi-towed-lines and adjacent Doppler bins and beams that cover the multi-path Doppler spread due to motion using adaptive MFP. A study of STAMP performance in the towed-array forward-looking problem will be discussed. In this problem, the own-ship signal and its bottom scattered energy can be treated as stationary interference with a moving target at constant speed within processing interval of a few minutes.

1. Introduction

Element-space pre-Doppler STAP[2] is two-dimensional fully adaptive processing that coherently combines the signals from the elements of an array and the multiple snapshots of coherent signals, to obtain large spatial and temporal signal gain, to suppress interference, and to provide target detection in azimuth and velocity. Computational complexity and the need to estimate the interference from limited snapshots make it impractical. The adjacent-filter beamspace post-Doppler STAP is a reduced-dimension partially adaptive approach. It performs a Doppler filtering with a temporal Fourier transform and a spatial filtering with the conventional beamforming before adaptive processing. The adaptive processing is done in a selected sub-space including a few beams and a few Doppler bins.

In the complex multi-path underwater environment, the signal will spread over many beams (especially when the array is steered away from broadside) and over many Doppler bins if a long estimation time is used. Without combining these bins a processor will encounter severe signal degradation. STAMP is different from the beamspace post-Doppler STAP in that it uses a propagation code to model the signal spread over beam and Doppler bins and coherently combines them. This new approach should provide improvement in signal estimation, while providing range and depth localization.

Single-element pre-Doppler space-time MFP had been reported in ref.(1). In this work, we will study the performance of the beamspace post-Doppler space-time adaptive MFP through a simulation. In section 2, we will describe the STAMP processing and the simulation scenario for the forward-sector processing. The simulation results will be discussed in section 3, and a summary will be given in section 4.

2. STAMP processing and Forward-Sector Processing Simulation Geometry

Figure 1 shows the STAMP processing diagram for a multi-line array. It starts with the Fourier transform of phone time series $x_{kl}(t)$ into frequency domain $X_{kl}(f)$, $\mathbf{X}_k(f)=[X_{k1}(f) \ldots X_{kn}(f)]$ where k is the line index and l is the phone index. A conventional beamforming response $b_k(f,\theta)$ then is calculated at each frequency bin for each towed line. A long beam-space vector $\mathbf{B}(f)$ is formed with beam responses at selected beams and Doppler bins from all towed lines. The covariance matrix $\mathbf{R}$ is formed by the outer product of $\mathbf{B}(f)$ and ensemble averaged over a wide Doppler band. For MFP, replicas are generated with a propagation code and passed through the same Doppler processing and conventional beamforming, then forming the beam-space replicas. The adaptive weight vectors are calculated with the wide-band covariance matrix $\mathbf{R}$ and the beam-space replicas, then applied on each $\mathbf{B}(f)$ to get the adaptive narrowband response. It is

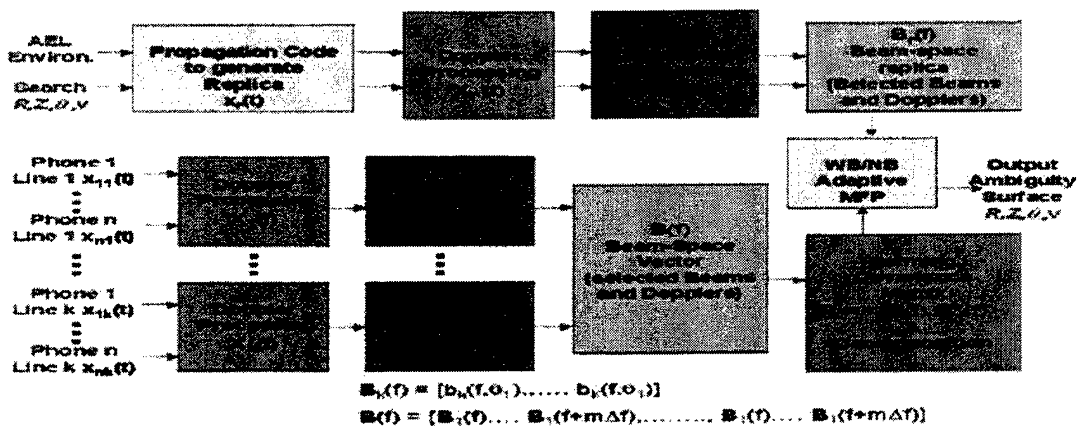

Figure 1: Space-Time Adaptive Matched-field Processing (STAMP)

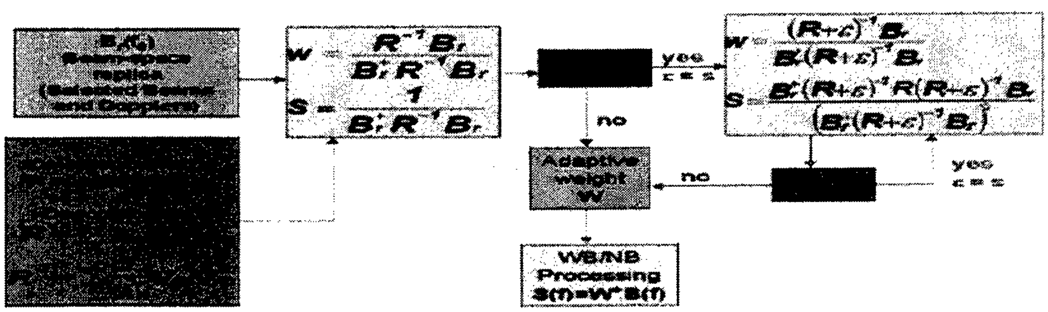

Figure 2: Wideband-Narrowband (WB/NB) Feedback-Loop White-Noise-Constrained (FLWNC) adaptive processing

noted that STAMP will be the same as conventional STAP when one replaces the propagation code with a plane-wave signal model.

Figure 2 shows the processing diagram of wideband-narrowband (WB/NB) Feedback-Loop White-Noise-Constrained (FLWNC) [3] adaptive processing. At each search cell, FLWNC iteratively adjusts the additive white noise until the white noise processing gain $|w|^2$ falls within the constraints δ_1 and δ_2. The calculated adaptive weight then is used to filter snapshots at each Doppler bin. This is called wideband-narrowband processing because the weight is calculated with the covariance matrix that is ensemble averaged over a broader Doppler band and then it is applied to narrowband snapshots at each Doppler bin.

Figure 3 shows the simulation geometry of forward-sector processing. The own-ship noise and its bottom bounce energy are treated as stationary broadband point-interference. The target at 90 m in depth broadcasts a narrowband signal and moves toward the tow ship with a relative speed of 6 kts. In the simulations, three array configurations were considered: single-Line, 4-Line-Sequential, and 4-Line-vertical. Each single-Line consists of 48 phones with a spacing of 2.25 m. The arrays are at a nominal depth of 90 m. The 4-Line-Sequential configuration connects four single-lines to form a long line. The 4-Line-Vertical configuration stacks 4 single-lines vertically with a vertical spacing of 10 m.

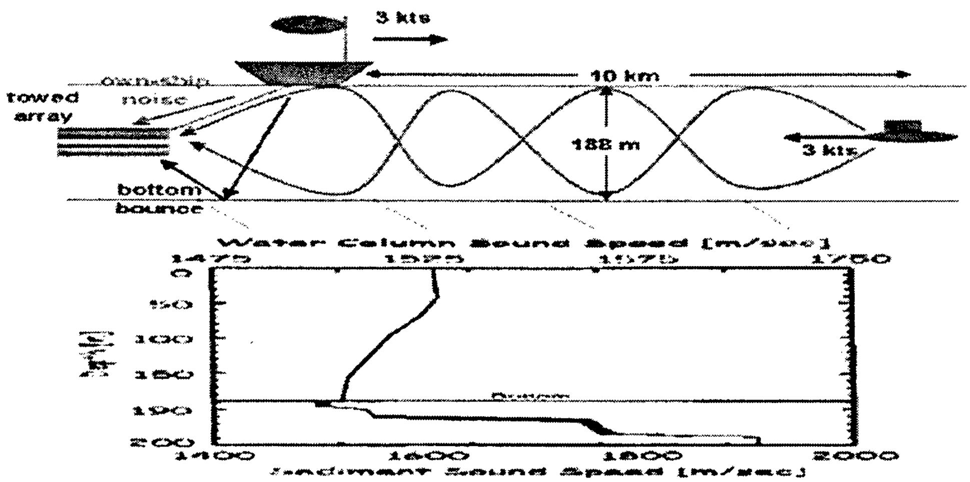

Figure 3: Simulation geometry, F=200 Hz, target(NB)=120 dB, own-ship(BB)=120 dB, bottom bounce (BB)=115 dB, white NL=120 dB, 0.1 random phase error, no environmental mismatch.

3. Simulation Results

From the conventional plane-wave beamforming of a single-Line, Figures 4 and 5 show beam/time responses (BTRs) and beam/Doppler responses of each signal component, respectively. The own-ship and the bottom interference arrive at relatively higher angles away from the forward endfire at 0°. The target component will be buried underneath the own-ship interference in the combined BTR, but with 256-sec integration time, it begins to separate from own-ship noise in the beam/Doppler response. The narrowband target signal is spread in Doppler and azimuth due to multi-paths that can be coherently combined with MFP to enhance detection and localization. This is the motivation of the STAMP study.

The top two panels in Figure 6 show the plane-wave beam spectrograms for single-Line steered at 10° off the forward endfire. The high-angle own-ship noise leaks into this shallow angle and causes the high noise background in the conventional beam spectrogram, but is significant suppressed by the adaptive processing. The bottom left panel shows the STAMP track-cell-gram that tracks the target location and the bottom right panel shows the maximum response over Doppler. The STAMP uses beams of 0° to 30° and 6 Doppler bins for 6-kt search. It is noted that STAMP processing provides 2-3 dB more signal gain than the plane-wave processing for single-Line and provides 8-9 dB more with 4Line-Vertical array.

Figure 7 shows the range tracking performance of the STAMP. In the simulation the target starts at 10 km and moves toward the towed ship. With single-Line, the conventional MFP does not provide range discrimination of the target. With adaptive MFP, single-Line STAMP starts to show the target track that is closing in range. The 4Line configurations help to suppress the range sidelobes, and the 4-Line-Vertical array provides a better performance than the 4-Line-Sequential array.

Figure 8 shows depth discrimination of STAMP range tracking with the 4-Line-Vertical array. The target track is formed only at the target depth of 90 meters. The target-related cascaded sidelobes are seen at other depths. Similarly, Figure 9 shows speed discrimination of STAMP range tracking with the 4Line-Vertical array. The target track is formed at the target speed of 3 m/s. Away from the target speed, the track becomes defocused and only target-related cascaded sidelobes are seen at search speeds far away from the target speed.

4. Summary

STAMP processing that combines STAP and MFP has been developed. Simulations show that STAMP coherently combines signal multi-path spread in azimuth and Doppler and greatly enhances the target detection as well as providing target range and depth classification and localization. In a future study, we will address how robust STAMP is against array shape error, frequency mismatch, and environmental mismatch as well as how STAMP performs in other tactical scenarios.

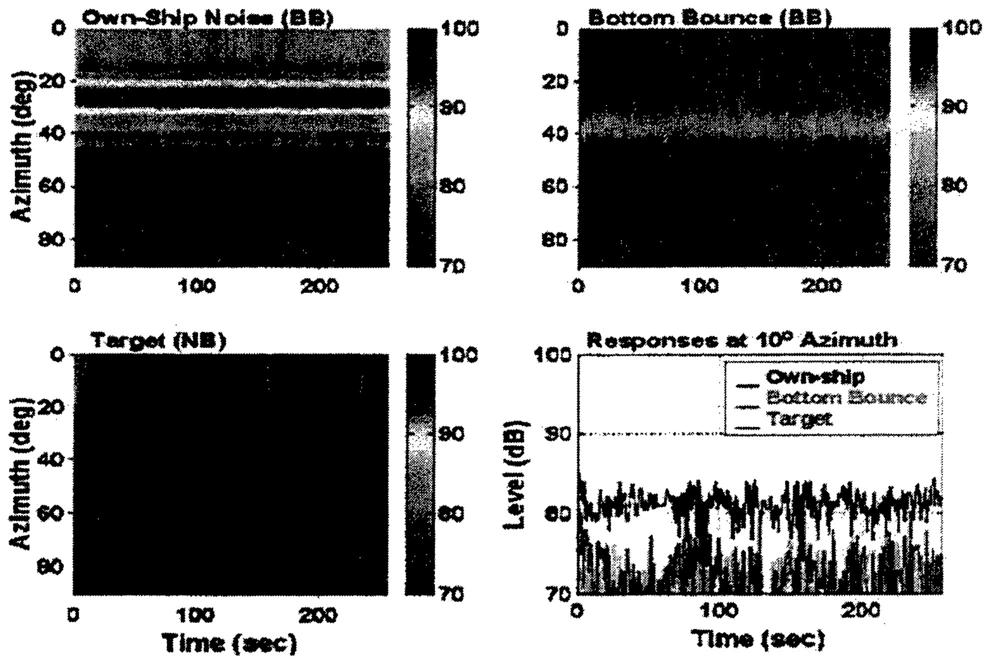

Figure 4 : Single-Line BTRs of each signal component.

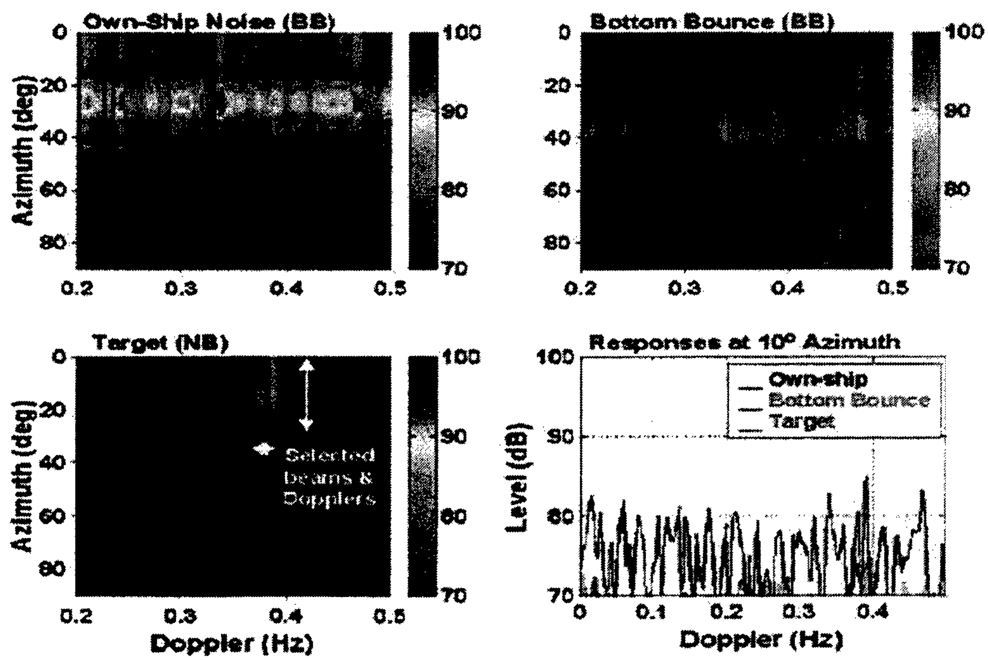

Figure 5: Single-Line Doppler/Azimuth responses of each signal component, 256-sec integration time.

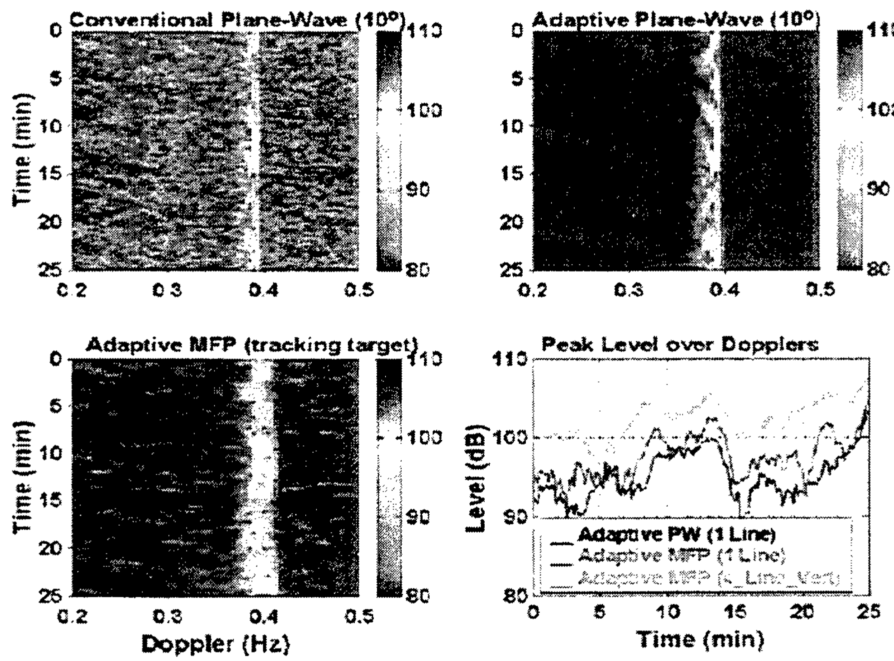

Figure 6: Single-Line beam/cell spectrograms.

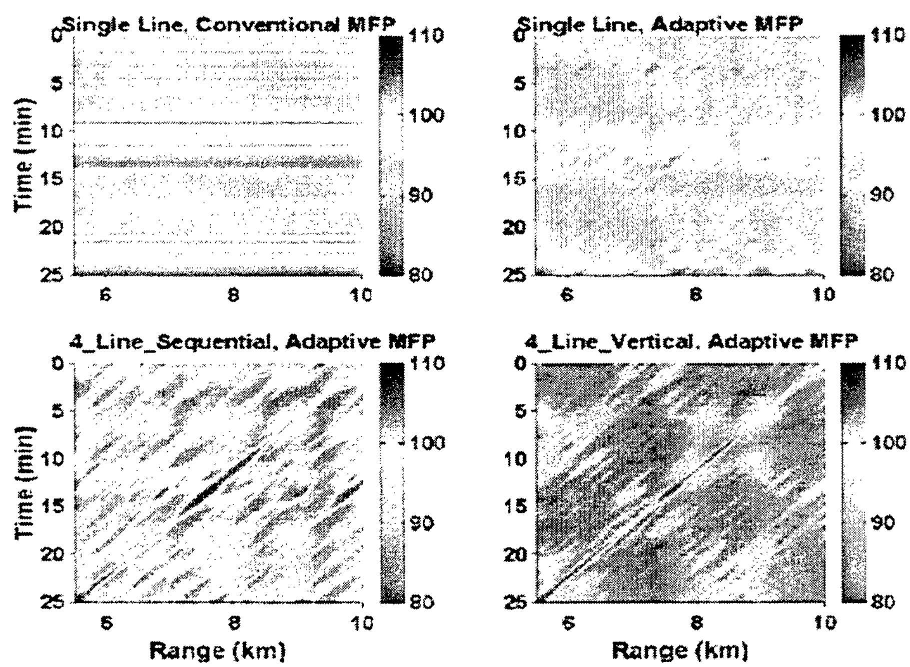

Figure 7: Array-size dependence of MFP range tracking search at target depth and target speed.

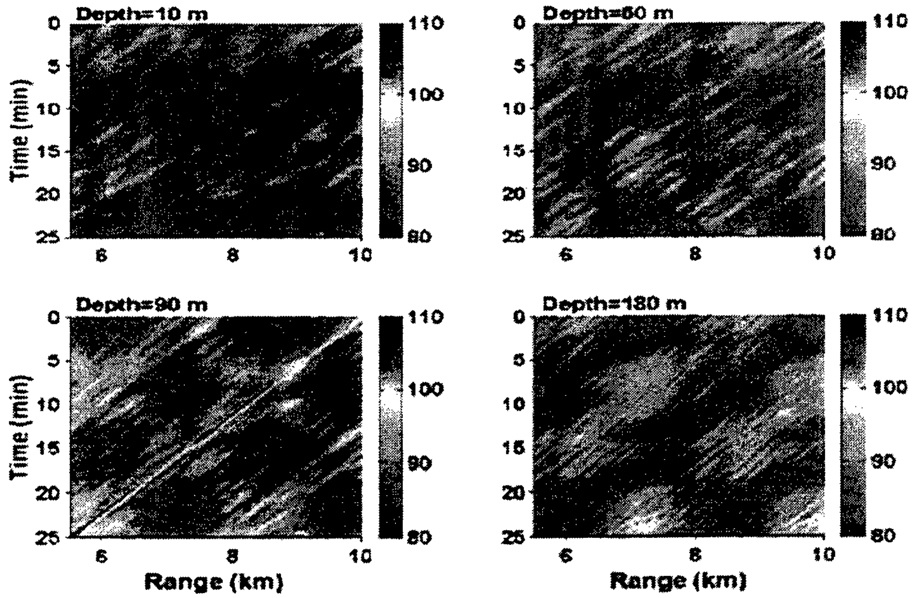

Figure 8: Depth discrimination of adaptive MFP range tracking, 4-Line-Vertical array search at target speed.

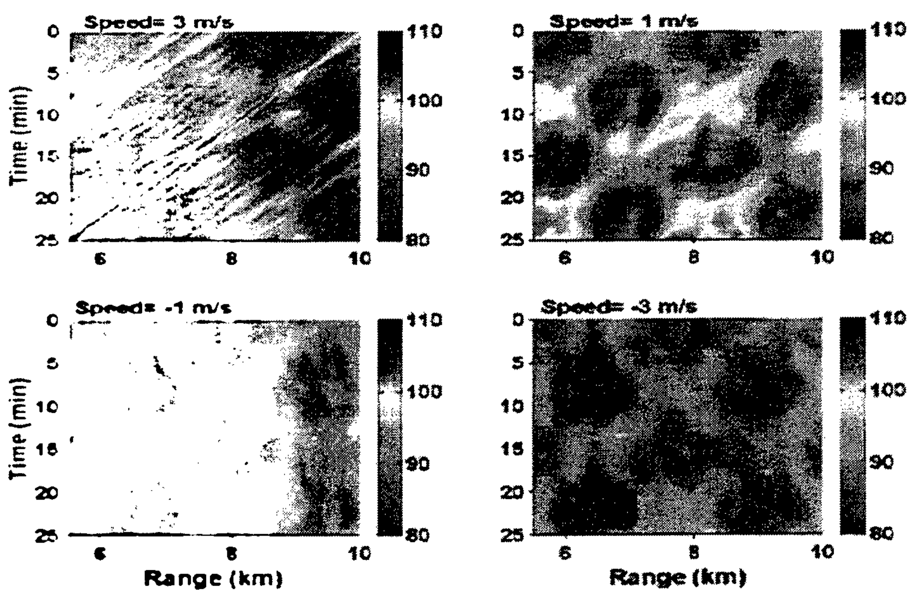

Figure 9: Speed discrimination of adaptive MFP range tracking, 4-Line-Vertical array search at target depth.

Reference:

(1) "Synthetic aperture matched-field processing," Yung P. Lee, JASA 100, pp2851 (1996).

(2) "Space-Time Adaptive Processing for Airborne Radar," J. Ward, Lincoln Laboratory Technical Report TR-1015, December 13, 1994.

(3) "Robust adaptive matched-field processing," Y. Lee, H. Freese, J. Hanna, and P. Mikhalevsky, Proc. IEEE Oceans'93, vol.3, pp 387-392, October, 1993.